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Citation for published version:

Van Wyk de Vries, M, Bingham, RG & Hein, A 2017, 'A new volcanic province: an inventory of subglacial volcanoes in West Antarctica', *Geological Society Special Publications*, vol. 461, pp. 231-248.
<https://doi.org/10.1144/SP461.7>

Digital Object Identifier (DOI):

[10.1144/SP461.7](https://doi.org/10.1144/SP461.7)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Geological Society Special Publications

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A new volcanic province: an inventory of subglacial volcanoes in West Antarctica

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Running title: Subglacial volcanoes in West Antarctica

1 **Abstract**

2

3 The West Antarctic Ice Sheet overlies the West Antarctic Rift System about which, due to the comprehensive
4 ice cover, we have only limited and sporadic knowledge of volcanic activity and its extent. Improving our
5 understanding of subglacial volcanic activity across the province is important both for helping to constrain
6 how volcanism and rifting may have influenced ice-sheet growth and decay over previous glacial cycles, and
7 in the light of concerns over whether enhanced geothermal heat fluxes and subglacial melting may contribute
8 to instability of the West Antarctic Ice Sheet. Here, we use ice-sheet bed-elevation data to locate individual
9 conical edifices protruding upwards into the ice across West Antarctica, and we propose that these edifices
10 represent subglacial volcanoes. We use aeromagnetic, aerogravity, satellite imagery and databases of
11 confirmed volcanoes to support this interpretation. The overall result presented here constitutes a first
12 inventory of West Antarctica's subglacial volcanism. We identify 138 volcanoes, 91 of which have not
13 previously been identified, and which are widely distributed throughout the deep basins of West Antarctica,
14 but are especially concentrated and orientated along the >3000 km central axis of the West Antarctic Rift
15 System.

16 West Antarctica hosts one of the most extensive regions of stretched continental crust on the Earth,
17 comparable in dimensions and setting to the East African Rift System and the western U.S.A.'s Basin and
18 Range Province (see Fig. 1 and e.g., Behrendt et al., 1991; Dalziel, 2006; Kalberg et al., 2015). Improved
19 knowledge of the region's geological structure is important because it provides the template over which the
20 West Antarctic Ice Sheet (WAIS) has waxed and waned over multiple glaciations (Naish et al., 2009; Pollard
21 and DeConto, 2009; Jamieson et al., 2010), and this provides a first-order control on the spatial configuration
22 of the WAIS' ice dynamics (Studinger et al., 2001; Jordan et al., 2010, Bingham et al., 2012). The subglacial
23 region today is characterised by an extensive and complex network of rifts, which likely initiated at various
24 times since the Cenozoic (Fitzgerald, 2002; Dalziel, 2006; Siddoway, 2008; Spiegel et al., 2016), and which in
25 some locations may still be active (Behrendt, et al., 1998; LeMasurier, 2008; Lough et al., 2013; Schroeder et
26 al., 2014). Collectively, this series of rifts beneath the WAIS has been termed the West Antarctic Rift System
27 (WARS), and is bounded by the Transantarctic Mountains to the south (Fig. 1).

28

29 In other major rift systems of the world, rift interiors with thin, stretching crust are associated with
30 considerable volcanism (e.g., Siebert and Simkin, 2002). However, in West Antarctica, only a few studies have
31 identified subglacial volcanoes and/or volcanic activity (e.g., Blankenship et al., 1993; Behrendt et al., 1998;
32 2002; Corr and Vaughan, 2008; Lough et al., 2013), with the ice cover having deterred a comprehensive
33 identification of the full spread of volcanoes throughout the WARS. Improving on this limited impression of
34 the WARS' distribution of volcanism is important for several reasons. Firstly, characterising the geographical
35 spread of volcanic activity across the WARS can complement wider efforts to understand the main controls
36 on rift volcanism throughout the globe (Ellis and King, 1991; Ebinger et al, 2010). Secondly, volcanic edifices,
37 by forming "protuberances" at the subglacial interface, contribute towards the macroscale roughness of ice-
38 sheet beds, which in turn forms a first-order influence on ice flow (c.f., Bingham and Siegert, 2009). Thirdly,
39 volcanism affects geothermal heat flow and, hence, basal melting, potentially also impacting upon ice
40 dynamics (Blankenship et al., 1993; Vogel et al., 2006). Fourthly, it has been argued that subglacial volcanic
41 sequences can be used to recover palaeoenvironmental information from Quaternary glaciations, such as
42 palaeo-ice thickness and thermal regime (e.g. Smellie, 2008; Smellie and Edwards, 2016).

43

44 In this contribution, we present a new regional-scale assessment of the likely locations of volcanoes in West
45 Antarctica based on a morphometric (or shape) analysis of West Antarctica's ice-bed topography. Volcano
46 shape depends on three principal factors: (1) the composition of the magma erupted, (2) the environment
47 into which the magma has been erupted, and (3) the erosional regime to which the volcano has been
48 subjected since eruption (Hickson, 2000; Grosse et al., 2014; Pederson and Grosse, 2014). Magma
49 composition in large continental rifts generally has low-medium silica content with some more alkaline
50 eruptions (Ebinger et al., 2013). In West Antarctica, where most knowledge of volcanoes is derived from
51 subaerial outcrops in Marie Byrd Land, volcanoes are composed of intermediate alkaline lavas erupted onto

52 a basaltic shield, with smaller instances being composed entirely of basalt and a few more evolved
53 compositions (trachyte, rhyolite; LeMasurier et al., 1990; LeMasurier, 2013). We therefore consider it likely
54 that many structures in the WARS are also basaltic. Regarding the environment of eruption, subaerial basaltic
55 eruptions typically produce broad shield-type cones protruding upwards from the surrounding landscape
56 (Grosse et al., 2014). Under subglacial conditions, monogenetic volcanoes often form steeper-sided, flat-
57 topped structures made up of phreato-magmatic deposits draped on pillow lava cores and overlain by lava
58 fed deltas known as tuyas (Hickson, 2000; Pederson and Grosse, 2014; Smellie and Edwards, 2016). Larger,
59 polygenetic volcanic structures, give rise to a range of morphometries reflecting the multiple events that
60 cause their formation, but many also have overall “conical” structures similar to stratovolcanoes or shield
61 volcanoes (Grosse et al, 2014; Smellie and Edwards, 2016).

62

63 In the WARS the macrogeomorphology is dominated by elongate landforms resulting from geological rifting
64 and subglacial erosion. We propose here that, in this setting, the most reasonable explanation for any
65 “cones” being present is that they must be volcanic in origin. We define “cones” as any features that have a
66 low length-width ratio viewed from above; thus for this study we include cones even with very low slope
67 angles. Thus we use cones in this subglacial landscape as diagnostic of the presence of volcanoes. We note
68 that identifying cones alone will by no means identify all volcanism in the WARS. For example, volcanic
69 fissures eruptions, a likely feature of rift volcanism, will yield ridge forms, or “tindars” (Smellie and Edwards,
70 2016) rather than cones. Moreover, in the wet basal environment of the WAIS, the older the cone the more
71 likely it will have lost its conical form from subglacial erosion. Therefore, cones present today are likely to be
72 relatively young – though we cannot use our method to distinguish whether or not the features are
73 volcanically active.

74

75

76

77 **Methods**

78

79 Our underpinning methodology was to identify cones that protrude upwards from a digital elevation model
80 (DEM) of Antarctica’s subglacial topography, and to assess the likelihood that each cone is a volcanic edifice.
81 We undertook our analysis on the Bedmap2 DEM (Fretwell et al., 2013) domain encompassed by the WARS,
82 which incorporates all of West Antarctica, the Ross Ice Shelf, and the Transantarctic Mountains fringing East
83 Antarctica that flank the WARS (Elliott, 2013). Importantly, while Bedmap2 represents the state-of-the-art
84 knowledge of West Antarctica’s subglacial landscape, it is derived from variable data coverage, the vast
85 majority of the data being sourced from airborne radar sounding acquired along one-dimensional tracks.
86 Along the radar tracks the horizontal spacing of bed-elevation data points can reach a few m, but between
87 tracks the spacing is often several km. The DEM itself is presented as a 1 km gridded product, though the raw

88 data were initially gridded at 5 km (Fretwell et al., 2013). Therefore, while the DEM cannot capture the fine-
89 scale topography now routinely acquired by satellite and airborne altimetry, and which has been exploited
90 for multiple morphometric analyses (e.g., Pederson and Grosse, 2014; Lindback and Pettersson, 2015; Ely et
91 al., 2016), it nevertheless presents a workable starting point for identifying volcanic edifices. We consider
92 how some of the DEM's limitations can be overcome in our analysis below.

93

94 We defined a cone as an upwards protuberance from the DEM whose elongation ratio (width versus length)
95 < 1.5 . Over the domain, but excluding non-grounded ice (primarily the Ross Ice Shelf) where the subglacial
96 topography is poorly characterised, we first extracted cones protruding at least 100 m from the surrounding
97 terrain. The bed elevation uncertainties within the DEM prevent reliable identification of smaller edifices.
98 Elevation profiles across each cone were then extracted from Bedmap2 at multiple angles with respect to
99 the current ice flow direction (taken from Rignot et al., 2011). Where radar profiles directly traversed a cone,
100 we further cross-checked the shape of the bed directly from the raw data. This is part of our procedure for
101 accounting for any artefacts in Bedmap2, which involves corroborating our identified volcanoes with auxiliary
102 datasets. To assess the likelihood that the Bedmap2-extracted cones were (a) not merely interpolation-
103 induced artefacts, and (b) likely represent volcanoes, we implemented a scheme wherein points were
104 awarded where auxiliary data ground-truthed the bed DEM and/or gave greater confidence in a volcanic
105 interpretation. The assessment criteria are as follows, with points awarded for each and data-source
106 references given in Table 1:

107

108 (1) Whether a cone is found within 5km of the nearest raw ice-thickness data.

109

110 (2) Whether a cone is overlain by an upward-protruding prominence in the surface of the ice draped over
111 it. This criterion takes advantage of the fact that, under the right balance between ice thickness and ice-
112 flow speed, subglacial topographic prominences can be expressed at the ice surface (e.g., De Rydt et al.,
113 2013).

114

115 (3) Whether a cone is discernible as a feature at the ice surface in visible satellite imagery. Various recent
116 studies have demonstrated that subglacial features can be outlined by visible expressions in surface
117 imagery (e.g., Ross et al., 2014; Chang et al., 2015; Jamieson et al., 2016).

118

119 (4) Whether a cone is associated with a clear concentric magnetic anomaly. This depends on the potential
120 volcano having a pillow-lava core, rather than being composed solely of tuff. This is consistent with the
121 thickness of ice overlying the cones and the erodibility of tuff/tephra deposits. Strong geomagnetic
122 anomalies have long been suggested as evidence of subglacial volcanism in the WARS (eg: Behrendt et
123 al., 1998; Behrendt et al., 2002).

124

125 (5) Whether a cone is associated with a concentric free-air and/or Bouguer anomaly.

126

127 Each cone was assigned a final confidence factor value of between 0 and 5 by summing up the points from
128 the five indicators described above (Table 1).

129

130 **Results**

131

132 Our morphometric analysis of subglacial West Antarctica recovers a total of 178 conical structures located
133 beneath the grounded WAIS and along the WARS (Fig. 2; Table 2). Of these, 80% are located within 15 km of
134 the raw ice-thickness data measurements (Fretwell et al, 2013), and 30% are identified from the DEM at sites
135 where volcanoes, either active or inactive, have previously been identified (LeMasurier et al., 1990;
136 LeMasurier 2013; Wardell et al 2014). Many cones were crossed directly by radio-echo sounding flightlines,
137 allowing verification of their profiles (e.g., Fig. 3) – thus while there is, inevitably, some smoothing in the
138 Bedmap2 interpolation, the major features of interest are largely captured. One of our confidence tests for
139 volcanic interpretation of cones also takes into account proximity to the raw ice thickness measurements,
140 further discounting DEM interpolation as a disproportionate influence on the results.

141

142 The identified cones range in height between 100 and 3850 m, with an average relief of 621 m, including 29
143 structures > 1 km tall that are mainly situated in Marie Byrd Land and the central rift zone. The basal diameter
144 of the cones ranges between 4.5 and 58.5 km, with an average diameter of 21.3 km. Most of the cones have
145 good basal symmetry with 63% of the long to short axis ratios being < 1.2. Table 3 presents a more in depth
146 statistical analysis of the morphology of these features and compares them to a global volcanic database
147 (Grosse et al., 2014). Figure 4 shows 1:1 cross sections of three of the newly identified cones along with three
148 prominent shield volcanoes for comparison.

149

150 78% of the cones achieve a confidence score (from our 5-point scheme) > 3, and we therefore consider it
151 reasonable to interpret these 138 cones henceforth as subglacial volcanoes. (We note that 98% of the 47
152 previously identified volcanoes in West Antarctica (visible at the surface and listed by LeMasurier et al., 1990)
153 achieved a confidence score > 3.) The volcanoes are distributed across subglacial West Antarctica, but are
154 especially concentrated in Marie Byrd Land (1 cone per 11200 ± 600 km²); and along a central belt roughly
155 corresponding to the rift's central sinuous ridge (Behrendt et al., 1998) with 1 cone per 7800 ± 400 km². For
156 comparison the overall volcanic edifice concentration along the East African Rift is roughly 1 volcano per 7200
157 km², rising to 1 volcano per 2000 km² in the densest regions (Global Volcanism Program, 2013).

158

159 **Discussion**

160

161 *Morphometry as a tool for identifying subglacial volcanoes*

162

163 We consider here three main implications that arise from our findings. Firstly, our approach demonstrates
164 that it is possible to use morphometry on Antarctica’s subglacial DEM, crucially together with relevant
165 auxiliary information, to identify potential subglacial volcanic edifices beneath West Antarctica. Secondly, it
166 highlights that subglacial West Antarctica – and, in essence, the WARS – comprises one of the world’s largest
167 volcanic provinces (c.f., LeMasurier and Thompson, 1990; Smellie and Edwards, 2016), and it provides basic
168 metrics concerning the locations and dimensions of the main volcanic zones. Thirdly, it serves to highlight
169 the wide spread of subglacial volcanism beneath the WAIS, which may impact upon its response to external
170 forcing through affecting coupling of the ice to its bed, and may have implications for future volcanic activity
171 as ice cover thins.

172

173 To our knowledge, our study here is the first to apply morphometry to identify volcanic edifices on the
174 continental scale beneath Antarctica. The extent of this volcanism has only previously been inferred from
175 geophysical studies (Behrendt et al., 2002). Morphometry has been used widely elsewhere in volcanology,
176 for example to catalogue volcanic parameters such as height, base width and crater width (e.g. McKnight and
177 Williams, 1997; Pedersen and Grosse, 2014), or to reconstruct eroded volcanic edifices (Favalli et al., 2014).
178 It has been applied to resolve volcanic characteristics in subaerial, submarine (e.g. Stretch et al., 2006) and
179 extraterrestrial (e.g. Broz et al., 2015) settings. However, in all such cases volcanic morphometry has been
180 applied to DEMs assembled from evenly-distributed elevation measurements derived from sensors viewing
181 unobscured surfaces. For subglacial Antarctica, having confidence that the subglacial DEM that has been
182 constructed from non-random elevation measurements has sufficient resolution for the applied
183 interpretation is key. Recent years have witnessed increasing glaciological recovery of subglacial information
184 from morphometry. For example, seeding centres for glaciation of the WAIS (Ross et al, 2014) and the East
185 Antarctic Ice Sheet (Bo et al., 2009; Rose et al., 2013) have been identified by the preponderance of sharp
186 peaks, cirque-like features, and closely-spaced valleys relative to other parts of the subglacial landscape.
187 Elsewhere, landscapes of “selective linear erosion”, diagnostic of former dynamism in now-stable regions of
188 ice, have been detected from the presence of significant linear incisions (troughs) into otherwise flat higher
189 surfaces (plateaux) (Young et al., 2011; Jamieson et al., 2014; Rose et al., 2014). All of these studies have in
190 common that they have closely considered auxiliary evidence to the morphometry, and hence have not relied
191 on the surface shape alone, in coming to interpretations concerning landscape formation. We have shown
192 here that such a combined approach is also valid for locating and mapping numerous previously unknown
193 volcanic edifices across the ice-shrouded WARS.

194

195 *Extent and Activity of Subglacial Volcanism*

196

197 We have identified at least 138 likely volcanic edifices distributed throughout the WARS. This represents a
198 significant advance on the total of 47 identified volcanoes across the whole of West Antarctica, most of which
199 are visible at the surface and are situated in Marie Byrd Land and the Transantarctic Mountains (LeMasurier
200 et al., 1990). The wide distribution of volcanic structures throughout the WARS, along with the presence of
201 clusters of volcanism concentrated within the Marie Byrd Land dome, is markedly similar to the East African
202 Rift System, which is also > 2000 km in length and flanked by the Ethiopian and Kenyan domes (Fig 1b; Siebert
203 and Simkin, 2002; Ebinger, 2005). Morphologically, the volcanoes have volume-height characteristics and
204 basal diameters that closely match those of rift volcanoes around the world (Figure 5 and Table 3). Bearing
205 in mind that data paucity beneath the Ross Ice Shelf precluded meaningful analysis of a significant terrain
206 also considered to be part of the WARS, the total region that has experienced volcanism is likely to be
207 considerably larger than that we have identified here.

208

209 The activity of the WARS has been the subject of a longstanding debate with one side advocating a largely
210 inactive rift (LeMasurier, 2008) and others suggesting large-scale volcanism (Behrendt et al., 2002). The
211 arguments in favour of an inactive rift are based on the anomalously low elevation of the WARS compared
212 to other active continental rifts (LeMasurier, 2008; Winberry and Anandakrishnan, 2004) and the relative
213 absence of basalt pebbles recovered from boreholes (LeMasurier pers. comm., 2015). Conversely, high
214 regional heat fluxes (Shapiro and Ritzwoller, 2004; Schroeder et al., 2014), geomagnetic anomalies (Behrendt
215 et al., 2002), and evidence of recent subglacial volcanism (Blankenship et al., 1993; Corr and Vaughan, 2008)
216 suggest the rift is currently active. This study provides evidence of a large number of subglacial volcanoes,
217 with their quasi-conical shield volcano type geometries still intact. The largely uneroded nature of the cones
218 suggests that many may be of Pleistocene age or younger which supports the argument that the rift remains
219 active today.

220

221 From this study, we are not able to determine whether the different volcanoes are active or not; however,
222 the identification of multiple new volcanic edifices, and the improved regional sense of their geographical
223 spread and concentration across the WARS, may guide future investigation of their activity. Several previous
224 studies have suggested that the Marie Byrd Land massif is supported by particularly low-density mantle,
225 possibly comprising a volcanic “hotspot” (Hole and LeMasurier, 1994; Winberry and Anandakrishnan, 2004).
226 Tephra layers recovered from the Byrd Ice Core near the WAIS divide suggest multiple Marie Byrd Land
227 volcanoes were active in the Late Quaternary (Wilch et al., 1999), while recent seismic activity in Marie Byrd
228 Land has been interpreted as currently active volcanism (Lough et al., 2013). In the Pine Island Glacier
229 catchment, strong radar-sounded englacial reflectors have been interpreted as evidence of a local eruption
230 that occurred ~2000-2400 years ago (see Figure 3 and Corr and Vaughan, 2008) while, on the opposite rift
231 flank in the Transantarctic Mountains, Mount Erebus comprises a known active volcano located above

232 another potential volcanic hotspot (Gupta et al., 2009). Volcanism across the region also likely contributes to
233 the elevated geothermal heat fluxes that have been inferred to underlie much of the WAIS (Shapiro and
234 Ritzwoller, 2004; Fox Maule et al., 2005; Schroeder et al., 2014). The deployment of broadband seismics to
235 recover mantle structure beneath the WAIS is now showing great promise (e.g., Heeszel et al., 2016), and
236 our map of potential volcanic locations could help target further installations directed towards improved
237 monitoring of the continent's subglacial volcanic activity.

238

239 *Implications for Ice Stability and Future Volcanism*

240

241 The wide spread of volcanic edifices and possibility of extensive volcanism throughout the WARS also
242 provides potential influences on the stability of the WAIS. Many parts of the WAIS overlie basins that descend
243 from sea level with distance inland, lending the ice-sheet a geometry that is prone to runaway retreat (Alley
244 et al., 2015; Bamber et al., 2009). Geological evidence points to the likelihood that the WAIS experienced
245 extensive retreat during Quaternary glacial minima (Naish et al., 2009) and concurrently contributed several
246 metres to global sea-level rise (O'Leary et al., 2013). Currently the WAIS may be undergoing another such
247 wholesale retreat, as ice in the Pacific-facing sector has consistently been retreating from the time of the
248 earliest aerial and satellite observations (Rignot, 2002; McMillan et al., 2014; Mouginot et al., 2014). We do
249 not consider it likely that volcanism has played a significant role in triggering the current retreat, for which
250 there is compelling evidence that the forcing has initiated from the margins (Turner et al. submitted), but we
251 do propose that subglacial volcanism has the potential to influence future rates of retreat by (1) producing
252 enhanced basal melting that could impact upon basal ice motion, and (2) providing edifices that may act to
253 pin retreat.

254

255 On the first of these possibilities, some authors have suggested that active subglacial volcanism, through
256 providing enhanced basal melting that might "lubricate" basal motion, could play a role in WAIS instability
257 (Blankenship et al., 1993; Vogel et al., 2006; Corr and Vaughan, 2008). A possible analogy is provided by
258 subglacial volcanism in Iceland, where subglacial eruptions have been known to melt basal ice, flood the basal
259 interface, and induce periods of enhanced ice flow (e.g., Magnússon et al., 2007; Einarsson et al., 2016);
260 however, in Iceland's ice caps the ice is considerably thinner than in the WAIS and hence more prone to
261 subglacial-melt-induced uplift. Nevertheless, there is evidence to suggest that changes to subglacial water
262 distribution can occur beneath the WAIS, and that they can sometimes have profound impacts on ice-
263 dynamics: examples are ice-dynamic variability over subglacial lakes (e.g., Siegfried et al., 2016), or the
264 suggestion that subglacial water pulses may have been responsible for historical occurrences of ice-stream
265 piracy (e.g., Anandakrishnan and Alley, 1997; Vaughan et al., 2008). Much recent attention has focussed on
266 drainage of subglacial lakes comprising plausible triggers of such dynamic changes, but subglacial eruptions
267 may represent another pulsed-water source whose occurrence has rarely, if ever, been factored into ice-

268 sheet models. Even inactive or dormant volcanism has the potential to influence ice flow by increasing heat
269 flux to the subglacial interface; this may generate a basal melt cavity and enhance ice flow (Bourgeois et al.,
270 2000; Schroeder et al., 2014).

271

272 On the other hand, volcanic edifices, whether active or not, stand as significant protuberances which may act
273 geometrically as stabilising influences on ice retreat. Numerical models used to project potential rates of
274 WAIS retreat show that, once initiated, ice retreat will continue unabated as long as the ice bed is smooth
275 and downslopes inland, but that any increase in roughness or obstacle in the bed can act to delay or stem
276 retreat (Ritz et al., 2015; Nias et al., 2016). We have identified here a number of volcanic edifices sitting within
277 the WAIS' deep basins; these edifices, which likely owe their existence to volcanism, could represent some
278 of the most influential pinning points for past and future ice retreat.

279

280 Looking ahead, the thinning and potential removal of ice cover from the WARS volcanic province could have
281 profound impacts for future volcanic activity across the region. Research in Iceland has shown that with
282 thinning ice cover magma production has increased at depth as a response to decompression of the
283 underlying mantle (Jull and McKenzie, 1996; Schmidt et al., 2013). Moreover, there is evidence that,
284 worldwide, volcanism is most frequent in deglaciating regions as the overburden pressure of the ice is first
285 reduced and then removed (Huybers and Langmuir, 2009; Praetorius et al., 2016). Unloading of the WAIS
286 from the WARS therefore offers significant potential to increase partial melting and eruption rates
287 throughout the rifted terrain. Indeed, the concentration of volcanic edifices along the WARS could be
288 construed as evidence that such enhanced volcanic activity was a feature of Quaternary minima. This raises
289 the possibility that in a future of thinning ice cover and glacial unloading over the WARS, subglacial volcanic
290 activity may increase, and this in turn may lead to enhanced water production contributing to further
291 potential ice-dynamical instability.

292

293 **Conclusions**

294 By applying morphometric analysis to a digital elevation model of the West Antarctic Rift System, and
295 assessing the results with respect to auxiliary information from ice-surface expressions to aerogeophysical
296 data, we have identified 138 subglacial volcanic edifices spread throughout the rift. The volcanoes are widely
297 distributed in the broad rift zone with particular concentrations in Marie Byrd Land and along the central
298 WARS axis. The results demonstrate that the West Antarctic Ice Sheet shrouds one of the world's largest
299 volcanic provinces, similar in scale to East African Rift System. The overall volcano density beneath West
300 Antarctica is found to be one edifice per $18500 \pm 500 \text{ km}^2$, with a central belt along the rift's central sinuous
301 ridge containing one edifice per $7800 \pm 400 \text{ km}^2$. The presence of such a volcanic belt traversing the deepest

302 marine basins beneath the centre of the West Antarctic Ice Sheet could prove to be a major influence on the
303 past behaviour and future stability of the ice sheet.

304

305 **Acknowledgements**

306 We would like to thank John Smellie and Matteo Spagnolo for insightful and thorough reviews of a first draft
307 of this manuscript which contributed, we hope, to a much improved paper.

308

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499

500 **Figure Captions**

501 **Fig. 1.** a. Location of the main components of the West Antarctic Rift System and confirmed volcanoes (red
502 circles; after LeMasurier et al., 1990; Smellie and Edwards, 2016). b. Location of Holocene volcanoes (Red
503 Circles) in the Ethiopia/Kenya branch of the East African Rift (red shaded area). The majority of this activity
504 is aligned along the rift axis with occasional flank volcanism. Data from Siebert and Simkin(2002); Global
505 Volcanic Program (2013).

506 **Fig. 2.** Location map of conical edifices (circles) identified from Bedmap2 (greyscale background) across the
507 West Antarctic Rift System. The data are tabulated in Table 2. Circle colour represents the confidence factor
508 used to assess the likelihood of cones being subglacial volcanoes, and circle size is proportional to the cone's
509 basal diameter. Circles with black rims represent volcanoes that have been confirmed in other studies
510 (LeMasurier et al., 1990; Smellie and Edwards, 2016), generally those that have tips that protrude above the
511 ice surface.

512 **Fig. 3.** The upper panel shows an echogram from NASA’s Icebridge mission (Leuschen et al., 2014) that shows
 513 generally good agreement between a cone on the echogram and on the Bedmap2 data. The lower panel
 514 shows an echogram from Corr and Vaughan (2008) with basal topography picking out two cones; the dark
 515 layer above the bed is tephra believed to have erupted around 2000 years ago.

516 **Fig. 4.** Cross sections of three cones from this study (numbers 21, 60 and 91; see Figure 2 and Table 2 for
 517 more details and locations) and three prominent shield volcanoes, namely Mauna Kea (Hawaii), Erta Ale and
 518 Marsabit (East African Rift).

519 **Fig. 5.** Volume/height chart of the cones from this study (crosses) superimposed over data from volcanoes
 520 worldwide (Grosse et al., 2014). The cones closely fit the morphology data for shield volcanoes, as would be
 521 expected for basalt-dominated rift volcanism.

522

523 **Table 1:** *Classification scheme used in assessing confidence that a cone extracted from Bedmap2 (Fretwell et*
 524 *al., 2013) can be interpreted as a volcano. Full scores are given in Table 2.*

Confidence assessment criterion	Dataset / source	Confidence score		
		0	0.5	1
1)Distance to nearest raw ice-thickness measurement	Figure 3 in Fretwell et al. (2013)	> 15 km	5 to 15 km	< 5 km
2)Expression in ice-surface DEM overlying identified subglacial cone	Bedmap2 ice-surface DEM (Fretwell et al., 2013)	No expression	Associated but off-centre anomaly	Direct overlying anomaly
3)Expression in MODIS imagery of ice surface overlying identified subglacial cone	MODIS Mosaic of Antarctica (Scambos et al., 2007)	No expression	Weak expression	Nothing visible
4)Magnetic anomaly data	ADMAP (Kim et al., 2007)	No anomaly	Weak anomaly	Clear anomaly
5)Gravity anomaly data	Studinger et al. (2002) Damiani et al. (2014) Scheinert et al. (2016)	No anomaly	Weak anomaly	Clear anomaly

525

526 **Table 2:** Tabulation of subglacial cone coordinates, dimensions, and volcanic-interpretation confidence
527 factors (see Table 1). The final column identifies whether the cone was a previously recognised volcano (Yes)
528 or a new discovery (No). Most of the previously identified volcanoes are catalogued in LeMasurier et al., 1991.

Number	Height (m)	Average Diameter (km)	Elongation Ratio	Volume (km ³)	Latitude	Longitude	Volcano Confidence Factor						Previously identified
							1	2	3	4	5	Sum	
1	800	26	1.08	106	-74.00	-80.38	0.5	1	1	0.5	0.5	3.5	Yes
2	600	14	1.15	23	-75.60	-81.60	1	1	0	1	0.5	3.5	No
3	300	7.5	1.14	3	-76.13	-83.53	1	0.5	0	1	0.5	3	No
4	300	18.5	1.18	20	-76.80	-85.27	1	0	0	1	0.5	2.5	No
5	650	24.5	1.04	77	-74.47	-86.40	0.5	0.5	0.5	0.5	0.5	2.5	No
6	350	17.5	1.19	21	-76.74	-87.50	1	0	0.5	1	0.5	3	No
7	250	17	1.27	14	-76.97	-87.89	1	0	0	1	0.5	2.5	No
8	950	29	1.07	157	-77.37	-88.10	1	0	1	0.5	0.5	3	No
9	300	19.5	1.05	22	-77.40	-89.38	1	0.5	1	0.5	0.5	3.5	No
10	350	15.5	1.07	17	-77.32	-90.34	1	0.5	1	0.5	0.5	3.5	No
11	600	32.5	1.17	124	-74.27	-89.58	0.5	0.5	0	0.5	0.5	2	No
12	550	36	1.06	140	-74.07	-91.18	0.5	0	1	0.5	0.5	2.5	No
13	450	27.5	1.20	67	-72.90	-91.30	0	1	0.5	0.5	0.5	2.5	No
14	500	22.5	1.25	50	-74.05	-92.90	1	1	0.5	1	0.5	4	No
15	1400	22.5	1.25	139	-73.73	-93.68	0.5	1	1	1	0.5	4	Yes
16	1450	19.5	1.29	108	-70.03	-125.97	1	1	1	1	0.5	4.5	Yes
17	1300	27	1.25	186	-73.89	-94.64	0.5	1	1	1	0.5	4	Yes
18	400	20	1.11	31	-78.03	-92.95	1	1	0	0.5	0.5	3	No
19	325	18.5	1.18	22	-78.21	-93.20	1	1	0	0.5	0.5	3	No
20	200	9.5	1.11	4	-78.20	-93.82	1	0.5	0	0.5	0.5	2.5	No
21	600	20.5	1.16	49	-78.15	-94.62	1	1	0	0.5	0.5	3	No
22	375	18.5	1.06	25	-78.68	-95.65	1	0	0.5	0.5	0.5	2.5	No
23	250	19	1.11	18	-78.52	-96.16	1	0.5	1	1	0.5	4	No
24	700	26.5	1.30	96	-78.13	-96.36	1	0.5	0	0.5	0.5	2.5	No
25	450	22.5	1.25	45	-78.00	-97.16	1	1	0	0.5	0.5	3	No
26	250	13.5	1.25	9	-78.67	-97.68	1	1	0	1	1	4	No
27	500	24.5	1.13	59	-74.97	-96.54	0.5	1	1	1	0.5	4	No
28	400	16.5	1.36	21	-74.86	-97.42	1	1	0	1	0.5	3.5	No
29	550	16	1.13	28	-75.07	-99.54	1	1	1	1	0.5	4.5	Yes
30	820	20.5	1.16	68	-74.73	-99.04	1	1	1	1	0.5	4.5	Yes
31	650	29	1.15	107	-75.07	-99.54	0.5	1	1	1	0.5	4	Yes
32	750	31	1.07	141	-74.03	-98.83	0.5	0	0	1	0.5	2	No
33	950	26	1.17	126	-74.21	-100.19	1	1	1	0.5	0.5	4	No
34	900	30	1.14	159	-74.51	-99.94	1	0	1	0.5	0.5	3	Yes
35	300	15.5	1.21	14	-74.72	-100.09	1	0	1	0.5	0.5	3	No
36	325	11.5	1.30	8	-75.24	-96.95	1	1	1	0.5	0.5	4	No
37	500	34	1.13	113	-72.19	-97.70	0	1	1	1	0.5	3.5	Yes
38	1025	40.5	1.19	330	-72.54	-97.61	0	0	0.5	1	0.5	2	Yes
39	400	20.5	1.16	33	-72.51	-98.38	0	1	1	1	0.5	3.5	Yes
40	525	28	1.15	81	-72.42	-99.23	0.5	1	1	1	0.5	4	Yes
41	325	20.5	1.16	27	-72.47	-99.94	0	1	1	1	0.5	3.5	Yes

42	550	33.5	1.16	121	-72.32	-101.07	0.5	1	1	0.5	0.5	3.5	Yes
43	225	11.5	1.30	6	-73.87	-103.30	0	0.5	1	1	0.5	3	No
44	675	26.5	1.12	93	-75.45	-103.29	1	1	1	0.5	1	4.5	No
45	350	9.5	1.38	6	-78.41	-101.96	1	0	0	0.5	0.5	2	No
46	575	23	1.19	60	-79.65	-101.80	1	0.5	0	1	0.5	3	No
47	275	12	1.18	8	-80.03	-101.60	1	0.5	0	0.5	0	2	No
48	250	13	1.17	8	-80.15	-101.46	1	0.5	0	0.5	0	2	No
49	175	21.5	1.15	16	-80.17	-103.39	0.5	0.5		0.5	0.5	2	No
50	325	22	1.20	31	-78.87	-102.91	1	0.5	0.5	0.5	0	2.5	No
51	225	27	1.16	32	-80.40	-105.61	0.5	1	0	1	0.5	3	No
52	1175	23	1.19	122	-78.74	-104.24	1	1	1	0.5	1	4.5	No
53	125	15	1.14	6	-77.61	-103.56	1	0.5	0.5	0.5	1	3.5	No
54	225	11.5	1.30	6	-82.05	-111.42	1	0.5	1	1	0.5	4	No
55	175	23	1.19	18	-77.43	-105.77	1	1	1	1	0.5	4.5	No
56	150	9	1.25	2	-77.70	-74.55	1	0.5	0	0.5	0	2	No
57	275	13.5	1.25	10	-78.46	-107.77	1	0.5	1	0.5	0	3	No
58	175	11	1.44	4	-76.72	-106.61	1	1	1	1	0.5	4.5	No
59	150	12.5	1.27	5	-76.87	-106.38	1	1	1	1	1	5	No
60	1200	33.5	1.16	264	-79.15	-111.05	1	0	1	1	1	4	No
61	450	14.5	1.23	19	-79.60	-111.45	1	0	0	1	0.5	2.5	No
62	200	6	1.40	1	-80.42	-114.00	1	0.5	0	1	0	2.5	No
63	425	10	1.22	8	-75.22	-106.92	0	0.5	0.5	0.5	0.5	2	No
64	450	18	1.12	29	-75.71	-108.40	1	0	1	0.5	1	3.5	No
65	375	14.5	1.23	15	-76.11	-107.68	1	0	1	0.5	1	3.5	No
66	400	17	1.27	23	-76.38	-109.78	1	0.5	1	1	1	4.5	No
67	325	10.5	1.33	7	-74.60	-110.62	0.5	1	1	0.5	0.5	3.5	No
68	400	19	1.24	28	-74.81	-110.57	1	1	1	0.5	0.5	4	No
69	350	14	1.33	13	-75.00	-110.43	0.5	1	1	0.5	0.5	3.5	No
70	750	30	1.14	132	-74.89	-111.26	1	1	1	0.5	0.5	4	No
71	2300	51.5	1.15	1197	-75.60	-110.70	1	1	1	0.5	1	4.5	Yes
72	3200	58.5	1.13	2149	-76.52	-112.02	1	1	1	1	1	5	Yes
73	250	15.5	1.07	12	-77.21	-111.92	1	0	0.5	0.5	1	3	No
74	1025	36	1.00	261	-77.72	-112.64	1	0.5	1	1	0.5	4	No
75	300	16	1.13	15	-77.67	-114.04	1	0.5	1	0.5	1	4	No
76	625	26	1.17	83	-77.80	-115.00	1	1	1	0.5	1	4.5	No
77	650	12	1.18	18	-78.08	-115.37	1	0	0.5	0.5	0	2	No
78	400	10.5	1.33	9	-78.11	-115.93	1	1	0.5	0.5	0	3	No
79	350	13.5	1.25	13	-78.93	-115.69	1	0	0.5	1	1	3.5	No
80	325	20.5	1.28	27	-79.68	-113.53	1	1	0	1	1	4	No
81	200	6	1.40	1	-80.38	-115.11	1	0.5	0	1	1	3.5	No
82	125	4.5	1.25	0	-80.38	-115.11	1	0.5	0	1	1	3.5	No
83	150	10	1.22	3	-80.34	-116.40	1	1	0	1	1	4	No
84	1750	31.5	1.10	341	-80.30	-117.49	1	1	1	1	1	5	No
85	800	20	1.22	63	-80.37	-118.90	1	0.5	1	1	1	4.5	No
86	750	18.5	1.31	50	-80.73	-117.56	1	1	1	1	1	5	No
87	150	10.5	1.33	3	-80.81	-118.65	1	1	0	1	1	4	No
88	225	13	1.36	7	-80.87	-120.70	1	0	0	1	1	3	No
89	100	9	1.25	2	-80.27	-117.62	1	1	0	0	0	2	No

90	150	10.5	1.33	3	-80.41	-118.65	1	1	1	1	0.5	4.5	No
91	550	29.5	1.19	94	-80.62	-120.12	1	0.5	1	1	1	4.5	No
92	250	12.5	1.27	8	-79.96	-120.20	1	1	1	1	0.5	4.5	No
93	150	10	1.22	3	-79.24	-119.18	1	1	0	1	0	3	No
94	100	8	1.00	1	-79.37	-119.00	1	1	0	0	0	2	No
95	125	7.5	1.14	1	-79.78	-115.18	1	0	0	0.5	0.5	2	No
96	100	8.5	1.13	1	-78.46	-120.28	1	0	0.5	1	1	3.5	No
97	1000	28.5	1.19	159	-77.54	-118.28	0.5	1	0.5	0.5	0.5	3	No
98	2600	49.5	1.11	1250	-76.96	-117.78	1	1	1	0.5	1	4.5	Yes
99	3850	58	1.11	2542	-76.07	-115.94	0.5	1	1	1	1	4.5	No
100	1350	27.5	1.29	200	-76.73	-125.76	1	1	1	1	0.5	4.5	Yes
101	1100	21	1.21	95	-76.93	-125.73	1	1	1	1	0.5	4.5	Yes
102	1050	20	1.11	82	-77.11	-125.89	0.5	1	1	0.5	0.5	3.5	Yes
103	2400	39	1.17	716	-77.32	-125.97	1	1	1	0.5	0.5	4	Yes
104	1100	22	1.20	104	-77.46	-126.85	0.5	1	1	0.5	0.5	3.5	Yes
105	550	29	1.15	91	-79.24	-128.12	0.5	0	1	0.5	0.5	2.5	No
106	600	17	1.27	34	-81.34	-125.35	1	0.5	0	1	1	3.5	No
107	150	11.5	1.30	4	-82.36	-127.50	1	1	1	1	1	5	No
108	600	25.5	1.13	77	-83.98	-133.02	1	0	1	0.5	0.5	3	No
109	500	39	1.11	149	-84.31	-131.87	1	0.5	1	0.5	0.5	3.5	No
110	125	11.5	1.30	3	-81.82	-128.45	1	0.5	1	1	1	4.5	No
111	100	8	1.29	1	-81.20	-129.58	1	1	0	0	0	2	No
112	550	42	1.15	190	-81.62	-130.38	1	0	1	1	1	4	No
113	275	28.5	1.19	44	-81.87	-130.76	1	0	0	1	1	3	No
114	350	29	1.07	58	-82.41	-134.85	1	1	1	0.5	0.5	4	No
115	150	10.5	1.33	3	-81.10	-132.52	1	0.5	1	1	1	4.5	No
116	400	31.5	1.25	78	-81.36	-133.60	1	1	1	0	0.5	3.5	No
117	100	6	1.40	1	-81.64	-134.55	1	0	0	0	1	2	No
118	250	15.5	1.07	12	-81.55	-135.48	1	0	1	1	0.5	3.5	No
119	550	21.5	1.15	50	-80.35	-131.14	1	1	1	0	1	4	No
120	250	11.5	1.30	6	-80.50	-134.03	1	0	1	1	1	4	No
121	950	36	1.12	242	-80.23	-134.29	1	0.5	1	1	0	3.5	No
122	250	30.5	1.03	46	-79.57	-132.88	1	0	0	0.5	0.5	2	No
123	325	23.5	1.24	35	-80.40	-136.32	0.5	0	1	1	1	3.5	No
124	400	29	1.00	66	-80.08	-138.89	0.5	0.5	0	1	0.5	2.5	No
125	275	32.5	1.10	57	-79.39	-137.82	0.5	0.5	1	1	0.5	3.5	No
126	125	17.5	1.19	8	-79.67	-138.15	0.5	0	1	0.5	0.5	2.5	No
127	250	19	1.11	18	-79.76	-139.69	1	0	0	0.5	0.5	2	No
128	400	24	1.18	45	-78.70	-137.18	0.5	1	0	0.5	0.5	2.5	No
129	300	10.5	1.33	6	-78.61	-137.87	0.5	0	1	0.5	0.5	2.5	No
130	600	25.5	1.13	77	-78.39	-139.25	1	0.5	1	1	0.5	4	No
131	425	39.5	1.08	130	-79.00	-142.10	1	0.5	0	0.5	0.5	2.5	No
132	700	31	1.00	132	-78.15	-140.91	1	0.5	1	0.5	0.5	3.5	No
133	675	22	1.00	64	-77.91	-140.89	1	1	1	0.5	0.5	4	No
134	2600	52.5	1.06	1406	-73.71	-126.54	0	1	1	1	0.5	3.5	Yes
135	400	28	1.15	62	-74.69	-127.78	0.5	1	1	0.5	0.5	3.5	No
136	200	4.5	1.25	1	-75.98	-128.21	0	1	1	1	0.5	3.5	Yes
137	1700	47.5	1.16	753	-76.11	-128.64	0	1	1	1	0.5	3.5	No

138	325	16	1.13	16	-75.80	-128.57	0	1	1	1	0.5	3.5	No
139	1500	19.5	1.17	112	-75.98	-129.11	0	1	1	1	0.5	3.5	Yes
140	450	5.5	1.20	3	-75.90	-129.29	0	1	1	1	0.5	3.5	No
141	1800	36	1.06	458	-75.98	-132.31	0.5	1	1	0.5	0.5	3.5	Yes
142	900	21	1.00	78	-76.24	-132.63	0.5	1	1	0.5	0.5	3.5	Yes
143	400	5	1.00	2	-76.22	-133.14	0	1	1	0.5	0.5	3	No
144	600	13	1.17	20	-76.27	-135.11	0	1	1	0.5	0.5	3	Yes
145	950	18.5	1.18	64	-76.27	-136.12	0	1	1	0.5	0.5	3	Yes
146	800	9.5	1.11	14	-75.88	-137.95	0	1	1	0.5	0.5	3	No
147	275	19.5	1.17	21	-75.62	-138.08	0	1	1	0.5	0.5	3	No
148	600	8.5	1.13	9	-78.09	-153.87	1	1	1	1	0.5	4.5	No
149	450	21.5	1.15	41	-78.13	-155.26	1	1	1	1	0.5	4.5	No
150	775	23	1.19	80	-77.88	-153.60	1	1	1	1	0.5	4.5	No
151	275	16.5	1.06	15	-77.89	-154.81	1	1	1	1	0.5	4.5	No
152	100	7	1.33	1	-78.19	-157.00	0	1	1	0.5	0.5	3	No
153	125	18	1.25	8	-82.11	-154.71	0	0	1	0.5	0.5	2	No
154	100	16.5	1.06	5	-81.96	-157.64	0	0	1	0.5	0.5	2	No
155	150	24	1.18	17	-81.53	-163.39	1	1	1	0.5	0.5	4	No
156	225	15	1.00	10	-78.00	-165.52	0	0.5	0.5	1	0.5	2.5	No
157	100	12	1.18	3	-77.18	-164.77	0	0.5	0.5	1	0.5	2.5	No
158	1400	34	1.13	318	-85.96	-163.98	0.5	1	1	0.5	0.5	3.5	Yes
159	400	10.5	1.33	9	-78.39	167.56	0.5	1	1	1	0.5	4	Yes
160	325	16.5	1.20	17	-78.50	166.04	0	1	1	1	0.5	3.5	Yes
161	1600	29	1.07	264	-78.61	165.08	0	1	1	1	0.5	3.5	Yes
162	2050	39.5	1.14	628	-78.73	163.67	0	1	1	1	0.5	3.5	Yes
163	2250	33	1.13	481	-77.78	168.67	0	1	1	1	0.5	3.5	Yes
164	1800	29.5	1.19	307	-77.70	166.83	0	1	1	1	0.5	3.5	Yes
165	1250	21	1.10	108	-77.49	166.78	0	1	1	1	0.5	3.5	Yes
166	425	22.5	1.14	42	-77.23	167.68	0	1	1	1	0.5	3.5	Yes
167	350	20.5	1.16	29	-77.18	166.94	0	1	1	0.5	0.5	3	Yes
168	750	16.5	1.20	40	-74.58	164.22	1	1	1	1	0.5	4.5	Yes
169	600	26.5	1.21	83	-73.80	169.69	0.5	1	1	1	0.5	4	Yes
170	950	33.5	1.09	209	-73.42	164.70	0	1	1	1	0.5	3.5	Yes
171	1550	34.5	1.16	362	-72.78	169.89	0	1	1	0.5	0.5	3	Yes
172	750	17.5	1.19	45	-71.93	170.41	0	1	1	1	0.5	3.5	Yes
173	500	25.5	1.13	64	-76.45	-165.16	0	0.5	0.5	0.5	0.5	2	No
174	450	34.5	1.09	105	-76.37	-166.16	0	0.5	0.5	0.5	0.5	2	No
175	450	13.5	1.25	16	-76.12	-72.41	0.5	1	1	1	0.5	4	Yes
176	400	9.5	1.38	7	-73.68	-78.91	0	1	1	0.5	0.5	3	No
177	550	20	1.22	43	-73.70	-79.43	0.5	1	1	1	0.5	4	Yes
178	300	17	1.27	17	-74.67	-78.72	0.5	1	1	1	0.5	4	Yes
Average	621	21.3	1.18	121	-77.56	-120.28	.69	.69	.71	.74	.57	3.40	

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531 **Table 3:** Statistical comparison of the morphologies of the cones identified in this study identified as
 532 volcanoes (a) with those from a global database of shield volcanoes (b; Grosse et al., 2014). The two are
 533 similar apart from the long-short axis ratio; our cones are, on average, more circular than shield volcanoes
 534 elsewhere. This could be linked to specific glaciovolcanic eruption mechanisms, but is most likely a data bias
 535 due to our detection methods excluding more elliptical edifices.

	Height (m)		Average Diameter (km)		Axis Ratio		Volume (km ³)		Confidence Factor
	a.	b.	a.	b.	a.	b.	a.	b.	a.
Average	701	940	21.9	17.1	1.19	2.11	144	150	3.75
Standard Deviation	641	670	10.7	11.6	0.09	0.81	345	371	0.56
Median	475	810	20.5	15.3	1.17	1.98	42	31	3.5
Minimum	100	100	4.5	2.3	1.00	1.13	0.5	0.2	3
Maximum	3850	3030	58.5	63.3	1.44	5.23	2542	3086	5

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